

# Detection of a 522 s Pulsation from the Transient X-ray Source Suzaku J0102.8–7204 (SXP 523) in the Small Magellanic Cloud

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## Abstract

During a routine calibration observation of 1E 0102.2–7219 in the Small Magellanic Cloud (SMC) carried out in October 2012 for the Suzaku satellite, we detected a transient X-ray source at (RA, Dec) = (01<sup>h</sup>02<sup>m</sup>47<sup>s</sup>, –72<sup>d</sup>04<sup>m</sup>54<sup>s</sup>) in the equinox J2000.0 with a positional uncertainty of  $\sim 1''.4$ . We conducted a temporal and spectral analysis of the source and found a coherent pulse signal with a period of  $522.3 \pm 0.1$  s, and a featureless spectrum described by a single power-law model with a photon index of  $1.0^{+0.1}_{-0.1}$  and a 0.5–10 keV luminosity of  $\sim 8.8 \times 10^{35}$  erg s<sup>–1</sup> at an assumed distance of 60 kpc. The Suzaku source is likely to be the counterpart of 2XMM J010247.4–720449, which has been observed several times, including during outburst by Swift. Based on the X-ray characteristics in our data, as well as the transient record and optical and near-infrared features in the literature, we conclude that this source is a high-mass X-ray binary pulsar with a Be star companion in the SMC, which is known to harbor an exceptionally large ( $\sim 80$ ) number of such sources in comparison to our Galaxy.

**Key words:** galaxies: Magellanic Clouds — stars: emission-line, Be — stars: pulsars: individual (Suzaku J0102.8–7204, SXP 523) — X-rays: bursts

## 1. Introduction and Summary

The Small Magellanic Cloud (SMC) has a mass of only  $\sim 10^{-2}$  of our own Galaxy, yet it hosts a comparable number of high-mass X-ray binary pulsars (Sturm et al. 2011). All but one of them are binary systems of a neutron star (NS) and a Be star (Coe et al. 2012). The extreme over-density of such sources infers an elevated star-forming activity about 25–60 Myr ago (Yokogawa et al. 2003; Antoniou et al. 2010).

Almost all these sources are recognized when they go outburst around the periastron passages in a highly eccentric orbit when the mass accretion rate to the NS increases. During the outburst, an X-ray pulsation of 1–1000 s (Knigge et al. 2011) is often detected, which gives a conclusive piece of evidence for identifying such sources. The orbital cycle is long (10–1000 days; Knigge et al. 2011), suggesting that there are an even larger number of Be/NS binary systems in the SMC.

In order to search for such sources yet to be discovered, X-ray survey observations were conducted several times using the ROSAT (Haberl et al. 2000; Sasaki et al. 2000), ASCA (Yokogawa et al. 2003), XMM-Newton (Haberl et al. 2012a), and Chandra (McGowan et al. 2008) X-ray observatories. X-ray monitoring observations were also made with the RXTE (Galache et al. 2008). All these

observations contributed to the detection of pulse signals from transient sources and to the localization for follow-up optical spectroscopy to reveal their Be/NS nature.

Less explored than survey and monitoring observations are routine calibration observations in the SMC. The galaxy hosts 1E 0102.2–7219 (E0102 hereafter), a young super-nova remnant, which is among the most often observed sources for calibrating in-orbit X-ray instruments because of its soft and line-dominated spectrum, stable flux, and good visibility throughout the year. The X-ray Imaging Spectrometer (XIS; Koyama et al. 2007) onboard the Suzaku satellite (Mitsuda et al. 2007) has observed this source once every few months for the purpose of monitoring the energy gain and the contamination build-up. As of writing, the XIS observed E0102 55 times with a total integration time of 1.7 Ms since 2005 August. In terms of the area (18'×18' for the XIS) times the exposure (20–30 ks every time), the depth of coverage is comparable to the SMC survey performed with the European Photon Imaging Counter (EPIC) on XMM-Newton (Haberl et al. 2012a). Therefore, such data sets provide a unique opportunity for searching bright transient sources and revealing their long-term behavior, as is illustrated in Haberl & Pietsch (2005); Eger & Haberl (2008); Takei et al. (2008).

In this Letter, we present the detection of a transient

source during two of our E0102 calibration observations with the XIS. We detected a coherent pulse of 522 s and obtained a power-law spectrum (Wada et al. 2012). The pulse period was also confirmed by a successive XMM-Newton observation (Sturm et al. 2013). Together with the drastic X-ray flux change and the features of the counterpart in the longer wavelengths found in previous studies, we conclude that this source is another Be/NS binary in the SMC.

## 2. Observations & Data Reduction

We conducted a calibration observation of E0102 on 2012 October 29, in which we recognized a bright transient source. The XIS is equipped with four X-ray CCD cameras at the foci of four X-Ray Telescope (XRT; Serlemitsos et al. 2007) modules, and has an imaging-spectroscopic capability in the 0.2–12.0 keV band. The four sets of cameras and telescopes are co-aligned with each other to provide a  $18' \times 18'$  field of view with a telescope half power diameter (HPD) of  $\sim 2'$ , independent of X-ray energies. Three of the CCD cameras (XIS0, 2, and 3) carry front-illuminated (FI) devices, while the remaining one (XIS1) carries a back-illuminated (BI) device. The devices have an energy resolution of 180 eV as a full width at half maximum (FWHM) at 5.9 keV as of the observation date. The FI and BI devices are superior to each other in the hard and the soft band response, respectively. The entire XIS2 and a part of the XIS0 cameras are dysfunctional since 2006 November and 2010 December, respectively, due to putative micro-meteorite hits, thus we used the remaining parts of the cameras. The total effective area amounts to  $\sim 800 \text{ cm}^2$  at 1.5 keV at the field center.

We operated the XIS in the normal clocking mode with a frame time of 8 s. Events were removed when they were taken during South Atlantic Anomaly (SAA) passages, elevation angles from the day Earth by  $\leq 5^\circ$  and from the night Earth by  $\leq 20^\circ$ . The net exposure time was 32.1 ks. We used the HEADAS software package<sup>1</sup> version 6.12 for the X-ray data reduction throughout this paper.

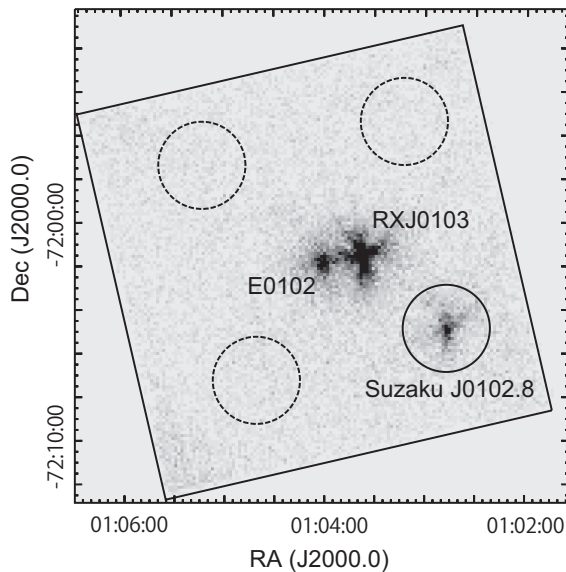
## 3. Analysis

### 3.1. Image Analysis

Figure 1 shows the XIS image in the 2.0–10 keV band. E0102 was observed at the center of the field. Another source RX J0103.6–7201 (RXJ 0103) can be found  $1.9'$  to the east. E0102 is a supernova remnant, which is predominantly bright below 2 keV, while RXJ 0103 is a high-mass X-ray binary, which is comparable in the hard-band brightness with E0102. Yet another source is apparent at a  $6.4'$  distance from E0102 displaced to the south west. This is a transient source as we did not recognize such a source in the previous XIS observations of E0102.

E0102 is an extended source, while RXJ 0103 is a point-like source, so we used the latter for the astrometric

correction by fitting the intensity profile with the point spread function. After shifting by  $(\Delta\text{RA}, \Delta\text{Dec}) = (27.''7, 2.''0)$ , we derived the position of the transient source to be  $(\text{RA}, \text{Dec}) = (01^{\text{h}}02^{\text{m}}47^{\text{s}}, -72^{\text{d}}04^{\text{m}}54^{\text{s}})$  in the equinox J2000.0 with an uncertainty of  $\sim 1.''4$ . We named the source Suzaku J0102.8–7204.8. We extracted source events from a  $2'$  radius circle around the source, and the background events from three circles of the same radius at an equal distance from E0102 (figure 1).



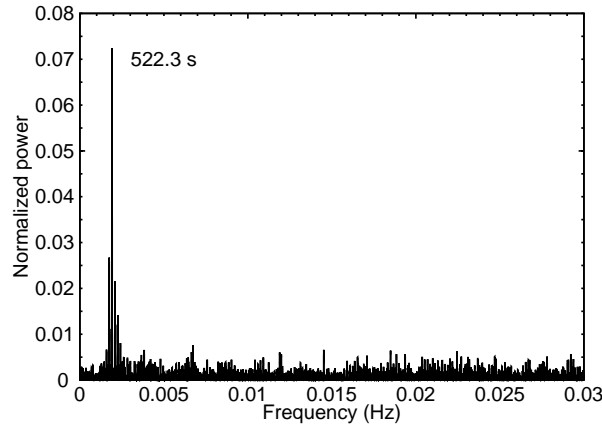
**Fig. 1.** XIS image in the 2.0–10 keV band after the astrometric correction. Events taken with XIS0, 1, and 3 are merged. The source and background extraction regions are shown with solid and dashed circles.

### 3.2. Temporal Analysis

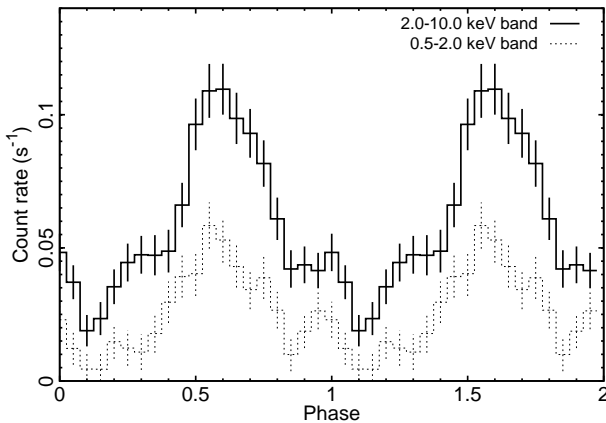
We first constructed the light curve of the transient source and confirmed that there were no flaring events nor any trends of flux variation during the observation. After a barycentric correction of the photon arrival times, we conducted a period search using the generalized Lomb-Scargle method (Zechmeister & Kürster 2009). Figure 2 shows the power spectral density using the events in the 0.5–10.0 keV band in the 0.01–31.25 mHz range. We found a peak at  $1.91 \times 10^{-3} \text{ Hz}$  with a statistical probability of  $< 10^{-10}$  for the peak to be a background fluctuation. We determined the fundamental period of  $522.3 \pm 0.1 \text{ s}$ . Following the naming convention by Coe et al. (2005), the source is alternatively called SXP 523<sup>2</sup>. Figure 3 shows the background-subtracted light curve folded by the period separately for the soft (0.5–2 keV) and hard (2–10 keV) bands. No significant change in the period was found between the two halves of the observation.

<sup>2</sup> It should be SXP 522, but we stick to the original naming by Haberl et al. (2012b) to avoid confusion.

<sup>1</sup> See <http://heasarc.gsfc.nasa.gov/docs/software/lheasoft/> for details.



**Fig. 2.** Power spectral density. A peak is found at  $1.91 \times 10^{-3}$  Hz.

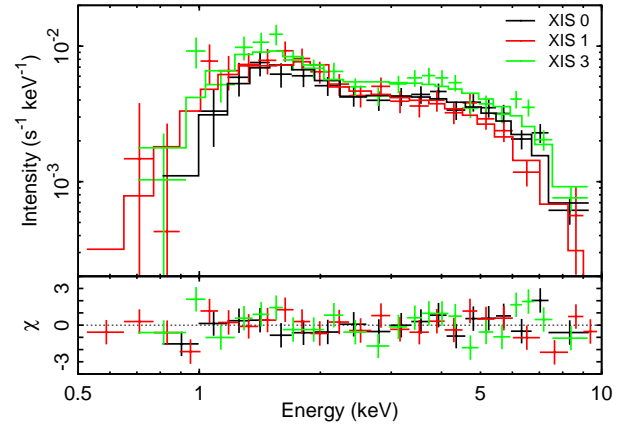


**Fig. 3.** Folded and background-subtracted light curve for two cycles in the 0.5–2 (dashed) and 2–10 (solid) keV bands.

### 3.3. Spectral Analysis

Figure 4 shows the background-subtracted X-ray spectrum. In order to fit the spectrum, we generated the detector and telescope response files using the `xismfgen` and `xissimarfgen` (Ishisaki et al. 2007) tools, respectively.

The spectrum is featureless, thus we fitted it with a power-law model attenuated by a photoelectric absorption model (`tbabs`; Wilms et al. 2000) using the Xspec software version 12.7.1. The free parameters are the power-law slope ( $\Gamma$ ), flux in the 0.5–10 keV band ( $F_X$ ), and the absorption column in the SMC ( $N_{\text{H}}^{\text{SMC}}$ ). The Galactic absorption column ( $N_{\text{H}}^{\text{Gal.}}$ ) was fixed to  $5.5 \times 10^{20} \text{ cm}^{-2}$  (Dickey & Lockman 1990). The metal abundance in the SMC was set to 0.2 solar (Russell & Dopita 1992). The spectrum was fitted quite well with such a simple model. The best-fit parameters are shown in table 1. The absorption-corrected luminosity in the 0.5–10 keV band is  $\sim 8.8 \times 10^{35} \text{ erg s}^{-1}$  assuming a distance of 60 kpc to the SMC (Mathewson 1985).



**Fig. 4.** XIS0 (black), 1 (red), and 3 (green) spectra in the 0.5–10.0 keV band. The upper panel shows the data with the crosses and the best-fit power-law model with the solid lines. The lower panel shows data residuals from the best-fit model.

**Table 1.** Best-fit parameters for the X-ray spectra.\*

Par. (unit)	2012 Oct 29	2012 June 25
$N_{\text{H}}^{\text{Gal.}\dagger}$ ( $10^{20} \text{ cm}^{-2}$ )	5.5 (fixed)	5.5 (fixed)
$N_{\text{H}}^{\text{SMC}\dagger}$ ( $10^{22} \text{ cm}^{-2}$ )	$2.3^{+0.7}_{-0.6}$	$0.5^{+1.3}_{-0.5}$
$\Gamma$	$1.0^{+0.1}_{-0.1}$	$1.3^{+0.2}_{-0.2}$
$F_X^\ddagger$ ( $10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$ )	$2.0^{+0.1}_{-0.1}$	$0.5^{+0.1}_{-0.1}$
$\chi^2_{\text{red}}/\text{dof}^\S$	1.01/59	1.30/29

\* The errors indicate a  $1\sigma$  statistical uncertainty.

$\dagger$   $N_{\text{H}}^{\text{Gal.}}$  and  $N_{\text{H}}^{\text{SMC}}$  are the hydrogen-equivalent column density of the Galactic foreground and the SMC, respectively.

$\ddagger$  The 0.5–10.0 keV band flux not corrected for the absorption.

$\S$  The reduced  $\chi^2$  ( $\chi^2_{\text{red}}$ ) and the degrees of freedom (dof).

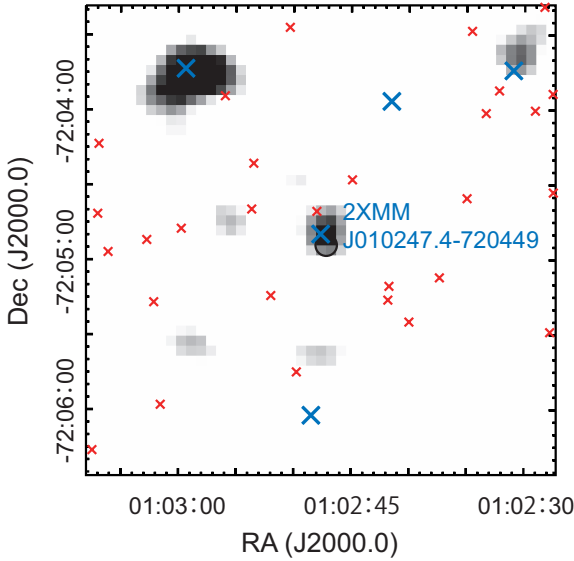
### 3.4. Other Data

We retrieved all the previous E0102 observations with the XIS and actually found a significant detection on 2012 June 25 with a count rate  $\sim 1/4$  of that recorded in 2012 October. We derived the pulse period of  $521.8 \pm 0.4$  s by epoch folding and the spectral parameters in table 1.

## 4. Discussion & Conclusion

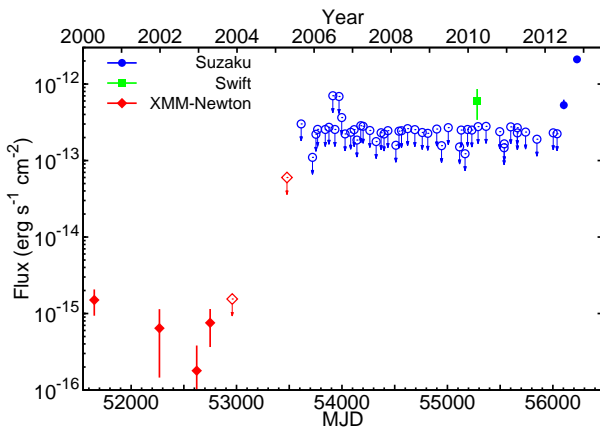
The region around E0102 has been observed numerous times also by other X-ray instruments. Figure 5 shows an XMM-Newton image around Suzaku J0102.8–7204. An XMM-Newton source named 2XMM J010247.4–720449 is found within the Suzaku error circle. 2XMM J010247.4–720449 is a transient source and very likely to be the same with the Suzaku source (Haberl et al. 2012b).

2XMM J010247.4–720449 is a Be/NS binary candidate from the X-ray spectral hardness and the association with an early-type star (Sturm et al. 2011). The occasional outburst is one of the characteristics of such sources. Indeed, this source was detected once in outburst by Swift in 2010 March 27, in addition to six times at quiescence during the SMC survey by XMM-Newton, and



**Fig. 5.** XMM-Newton EPIC image in the 0.5–10 keV band taken on 2000 April 16. The positions of XMM-Newton catalog (Watson et al. 2009) and 2MASS sources are shown respectively with blue and red crosses. The  $3\sigma$  positional error for the Suzaku source is shown with the circle at the center.

also in the stacked Chandra image at quiescence (Sturm et al. 2011). During the Swift outburst, the flux was  $(6.0 \pm 2.6) \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}$  in 0.2–10.0 keV, whereas at quiescence, the flux was  $2\text{--}3 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$  (Sturm et al. 2011). The long-term trend combining all these data (figure 6) shows a drastic flux change of the source by  $\sim 4$  orders of magnitude.



**Fig. 6.** Long-term change in the 0.5–10 keV flux. Upper limits ( $5\sigma$ ) are shown by open symbols with downward arrows. The XIS limits were derived in the 2–10 keV band to avoid readout streaks from the soft and bright source E0102.

During the Swift outburst in 2010, the X-ray spectrum was fitted with an absorbed power-law model with  $\Gamma = 0.9 \pm 0.5$  and  $N_{\text{H}}^{\text{SMC}} < 1.5 \times 10^{22} \text{ cm}^{-2}$ . In comparison with our results (table 1), the power-law index is consistent among the three measurements, while the SMC absorption is significantly higher in our October result, suggesting

that the circumstellar extinction was higher during the outburst of that epoch.

Sturm et al. (2011) identified the optical and near-infrared counterpart at the position consistent with the X-ray source, and their magnitudes are ( $U$ ,  $B$ ,  $V$ , and  $I$ ) = (14.69, 15.75, 16.00, and 16.30) mag by Zaritsky et al. (2002) and ( $J$ ,  $H$ , and  $K_s$ ) = (16.58, 16.52, and 16.61) mag by Kato et al. (2007), respectively. Sturm et al. (2011) also retrieved the  $I$ -band light curve of the source in the optical gravitational lensing experiment, in which the magnitude was constant at  $\sim 16.25$  mag and brightened to  $\sim 15.7$  mag on 2009 May 2. Haberl et al. (2012b) reported detection of an  $H\alpha$  signature in emission with an equivalent width of  $-4 \text{ \AA}$  on 2012 December 8. The magnitude, color, brightening trend, and presence of the  $H\alpha$  emission line confirm the hypothesis that this star exhibits a Be phenomena.

In summary, the multi-wavelength characteristics are quite typical of those for the high-mass X-ray binary pulsars with a Be star companion in the SMC (Coe et al. 2005; Laycock et al. 2010). Our detection of a coherent pulse signal from the source concludes that this is the case.

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